Exploration and Control of Condensed Matter Qubits

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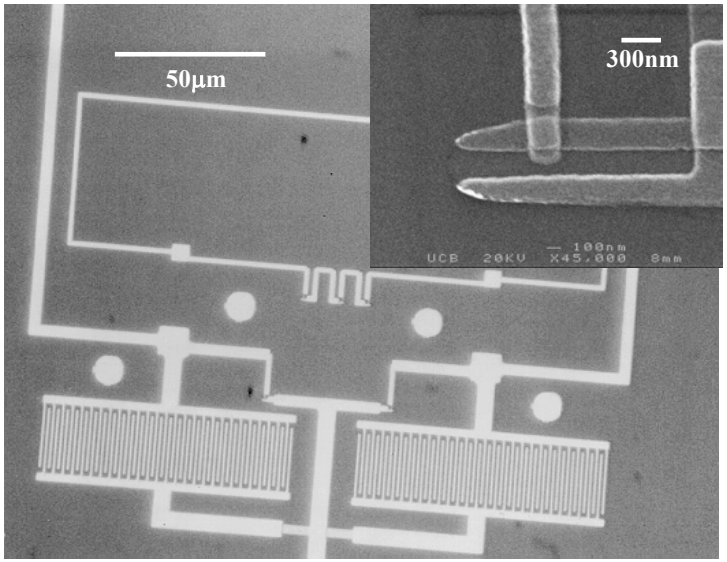
A flux qubit consists of a superconducting loop interrupted by one or more Josephson junctions. With appropriate parameters and at low temperatures – say 30 mK – the qubit should exist in a superposition of two states, one with a clockwise supercurrent $|0\rangle$ and the other with an anticlockwise current $|1\rangle$. The energy levels of the two superposed states $\alpha|0\rangle + \beta|1\rangle$ and $\alpha|0\rangle - \beta|1\rangle$ are separated, resolving the degeneracy of the states $|0\rangle$ and $|1\rangle$. Observation of the superposed states and understanding of the sources of decoherence remain a major challenge; but, in the long term, the flux qubit may provide a key element for quantum computers. A major problem is the fact that one needs highly underdamped Josephson junctions to minimize the dissipation experienced by the qubit, but overdamped junctions (low parallel shunt resistance) to achieve a high fidelity readout. We have addressed this dilemma by providing the junctions with frequency-dependent shunts – a nanofabricated resistor and capacitor in series.



Using electron-beam lithography we have nanofabricated prototype devices, and found that the resolution at 37 mK is excellent, more than sufficient for single-shot readout of the flux qubit. Experiments on devices with a qubit fabricated inside the dc SQUID on the same chip are in progress.

Synthesis and Control of Molecular Machine Components

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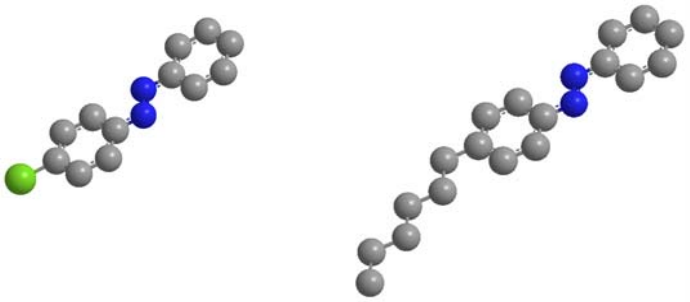
The development of molecular machines offers great promise for creating new technologies at the nanoscale. In order to achieve our goal of creating functional molecular machines, we are developing new techniques for synthesizing, characterizing, and assembling molecular nanostructures. We are pursuing this goal by synthesizing new molecular components, designed to act as building blocks for more complex nanomechanical structures. Actuation of these molecular machines will be achieved through optical and electronic stimulation of molecular components, while assembly will be performed via three methods: scanned probe molecular manipulation, self-assembly, and integration into lithographic structures. To date we have successfully synthesized and characterized functionalized azobenzene molecules to be used as opto-motional transducers. The idea here is to take advantage of the reversible photo-isomerization of this molecule (trans to cis) that occurs for optical stimulation at wavelengths 360nm and 430 nm.



Two functionalized azobenzene molecules synthesized to act as molecular components. Azobenzene is shown functionalized with a chlorine group and an alkyl chain.

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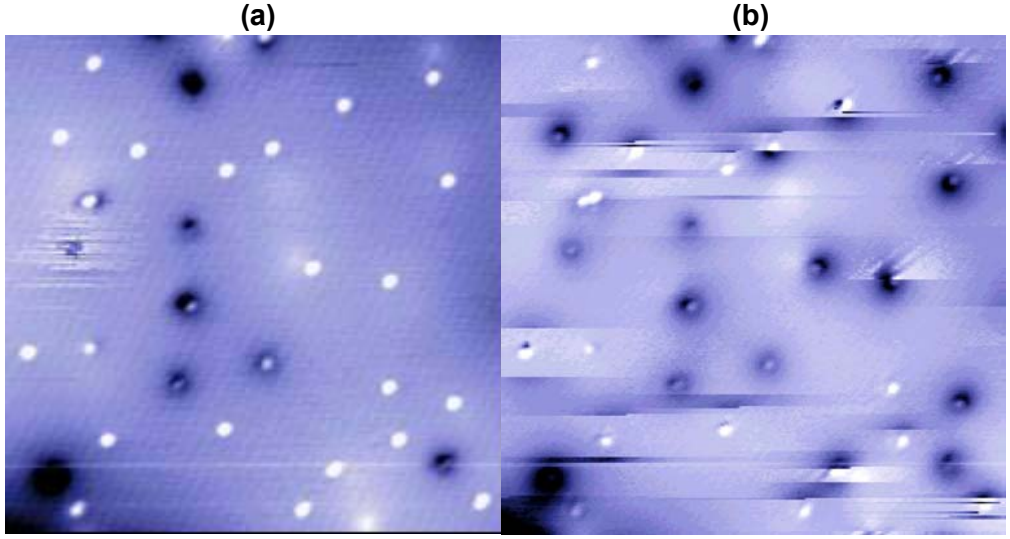
We are exploring the possibility of controlling the electronic state of individual impurity atoms in semiconductors with a view toward the application of such quantum states to quantum computing. We have recently demonstrated the capability to 'switch' the electronic state of single atom defects on the surface of GaAs. The adjacent figure shows several surface defect states (single As anti-sites most likely) which are nascent on the left (where each bright dot is an atomic scale defect) and are switching atomic scale electronic configuration under tip influence on the right. To carry out this research we have developed an atomic-resolution STM system operating at 15 millikelvin in fields up to 9 Tesla and with wavefunction imaging capabilities. It is the only such instrument in the world at present.



This STM image shows individual defect states on the GaAs(110) surface (a) before and (b) after being "switched" into a new electronic configuration by the tip of an STM at T = 15 millikelvin (image size 200Å x 200Å).

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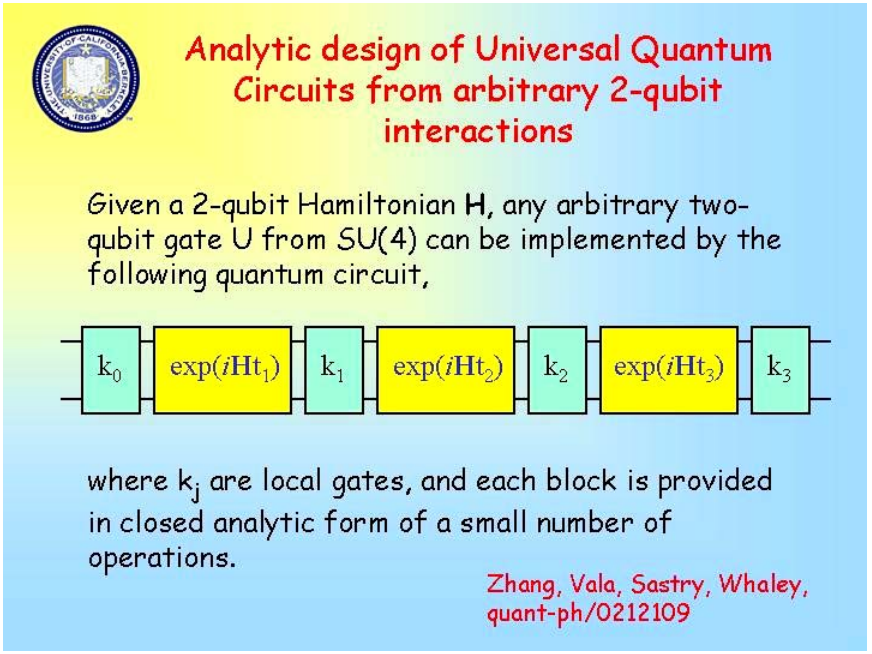
We have developed a geometric approach to the analysis of non-local two-qubit operations that are central to efficient quantum logic and quantum computation. This approach has led to the analytic construction of an efficient (small) quantum circuit for implementation of any arbitrary two-qubit operation starting from any given two-qubit entangling operation plus local gates. Two publications describing this work are shown below.



J. Zhang, J. Vala, S. Sastry and K. B. Whaley, "Geometric theory of non-local two-qubit operations", Phys. Rev. A 67, 0323XX (2003); quant-ph/0209120.

J. Zhang, J. Vala, S. Sastry and K. B. Whaley, "Exact two-qubit universal quantum circuit", submitted to Phys. Rev. Lett.; quant-ph/0212109.

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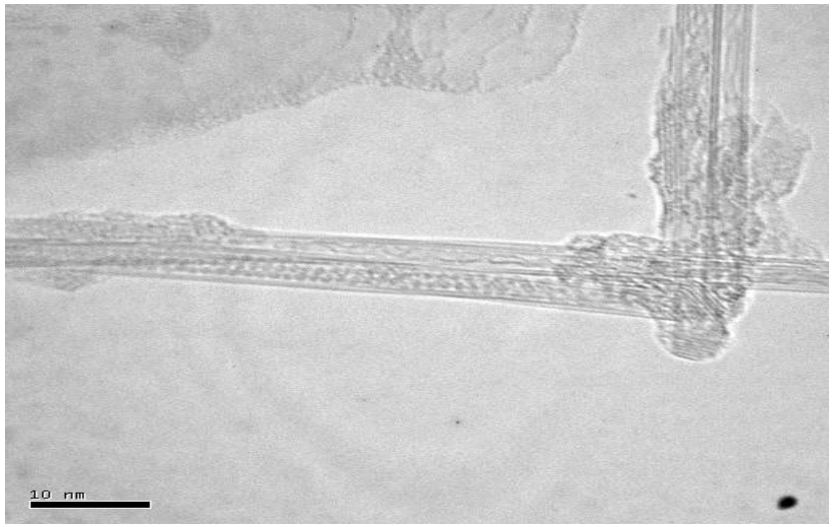
We have successfully synthesized nanoscale solid state structures that may lead to solid state qubit realizations. Our approach is to use hollow large band gap boron nitride nanotubes and fill them with spherical molecules (in this case C_{60} molecules). One-dimensional C_{60} chains and new C_{60} "crystals" have been formed within the tubes. The next step is to use filling species with magnetic signatures (for example selected endohedral fullerenes).



This TEM image shows two independent BN nanotubes (roughly horizontally aligned), the upper one partially filled with amorphous BN, and the lower one filled with a crystalline array of C-60 molecules (scale bar is 10nm).

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Magnetic molecules form a possible "qubit" system and are being probed via scanning tunneling microscopy. Magnetic molecules are exciting because they can be tuned using chemical synthesis techniques to change the interior magnetic moment and the coupling to exterior electrodes. Here we show the local spectroscopic response of an individual Gd@C82 endohedral molecule. The interior Gd ion has a strong magnetic moment (7 Bohr magnetrons). We are currently trying to identify the peaks in the spectral response, which may indicate magnetic behavior for the Gd ion. Future studies will involve spin-polarized scanning tunneling microscopy to directly detect magnetic dynamical behavior of the Ångstrom scale.

STM Spectroscopy of $Gd@C_{82}$ on Ag(100)